

Open-flavor strong decays of open-charm and open-bottom mesons in the 3P_0 model

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We provide results for the open-flavor strong decays of open-charm (D and D_s) and open-bottom (B , B_s and B_c) mesons. The decays are calculated in a modified version of the 3P_0 pair-creation model, assuming harmonic oscillator wave functions. The spectra of open-charm and open-bottom mesons used in the calculations are computed within the relativized quark model developed by Godfrey and Isgur. The results are compared with the existing experimental data.

PACS numbers: 12.39.Pn, 13.25.Ft, 14.65.Dw, 24.85.+p

I. INTRODUCTION

Since the discovery of the J/Ψ and Υ resonances in the 1970s, heavy meson physics (including the physics of charmonia [1, 2], bottomonia [3, 4], open-charm [5, 50] and open-bottom [7–9] mesons) has been extensively studied, and is still a subject of intensive theoretical and experimental research [10, 11]. Recently, both the charmonium and bottomonium spectra have been enriched by the discovery of new particles [10, 11]; also the knowledge of open-charm and open-bottom mesons has improved substantially with the experimental observation of new resonances, including the $D_0^*(2400)$ [12, 13], $D_1(2430)^0$ [13] and $B_1(5721)$ [14, 15]. See Table I. The properties and quantum numbers of a large part of the newly-observed open-charm and open-bottom mesons are still not well established. Some examples are $D_J^*(2600)$ [10, 16], $D(2740)^0$ [10, 17] and $B_J(5970)^0$ [10, 18]. This has led to remarkable theoretical efforts to provide the experimentalists with predictions regarding spectrum, decay modes, and so on, and attempts to make quark model assignments for observed new states.

Important information on mesons can be extracted from their possible decay modes, including electromagnetic, weak and strong decays. The possibility to provide a theoretical description of strong (open- and hidden-flavor) decays relies mainly on phenomenological models, because the operators that describe the strong transitions between hadrons, arising from non-perturbative QCD, are essentially unknown. In the open-flavor case, they include “hadrodynamical” models, pair-creation models and elementary meson emission models [19].

In this paper, we focus on the 3P_0 pair-creation model, in which the decays proceed via the production of $q\bar{q}$ pairs with vacuum quantum numbers, i.e. $J^{PC} = 0^{++}$, somewhere in the hadronic medium [20]. An important feature of the 3P_0 model, apart from its simplicity, is that

it provides the gross features of several transitions with only one free parameter, the pair-creation strength γ_0 , which is a free constant to be fitted to the experimental data. More recent studies have also discussed the possibility of substituting the constant pair-creation vertex of the model with a more refined one [21–26]. Extensively applied to the study of open-flavor strong decays of light mesons [21, 27, 28] and baryons [29–31], the 3P_0 pair-creation model has also been used to compute the decays of charmonia [32–35], bottomonia [36], open-charm [26, 37, 38] and open-bottom [39] mesons.

The aim of the present paper is to provide a classification of open-charm and open-bottom mesons in terms of their masses, calculated within Godfrey and Isgur’s relativized model [40, 41], quantum numbers, and open-flavor amplitudes, evaluated within a modified version of the 3P_0 pair-creation model [34–36, 42]. As widely shown by previous quark model calculations, we expect to obtain a good overall description of the properties of these mesons, with the possible exception of states close to meson-meson decay thresholds, like $D_0^*(2400)$ and $D_{s0}^*(2317)$ [43, 44]. Indeed, it is well known that the quenched approximation may fail for states in the region around the opening of meson-meson decay thresholds, where it is believed that continuum-coupling effects play an important role [34, 35, 45–48]. A study of these particular states in the context of coupled-channel models will be addressed in a future publication.

II. FORMALISM

A. 3P_0 pair-creation model

In the 3P_0 pair-creation model, the open-flavor strong decay of a hadron A into hadrons B and C takes place in its rest frame, via the creation of an additional $q\bar{q}$ pair characterized by $J^{PC} = 0^{++}$ quantum numbers [20, 29, 49]. The decay widths $A \rightarrow BC$ are calculated as

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State	J^P	Exp. Mass [MeV]	$\Gamma_{\text{tot}}^{\text{exp}}$ [MeV]
$D^*(2007)^0$	1^-	2006.85 ± 0.05	< 2.1
$D_0^*(2400)^0$	0^+	2318 ± 29	267 ± 40
$D_1(2420)^0$	1^+	2420.8 ± 0.5	31.7 ± 2.5
$D_1(2430)^0 \dagger$	1^+	$2427 \pm 26 \pm 25$	$384_{-75}^{+107} \pm 74$
$D_{s1}(2460)^\pm$	1^+	2459.5 ± 0.6	< 3.5
$D_{s1}(2536)^\pm$	1^+	2535.10 ± 0.06	$0.92 \pm 0.03 \pm 0.04$
$D_2^*(2460)^0$	2^+	2460.57 ± 0.15	47.7 ± 1.3
$D_0(2550)^0 \dagger$	0^-	2564 ± 20	135 ± 17
$D_{s2}^*(2573)^\pm$	2^+	2569.1 ± 0.8	16.9 ± 0.8
$D_{s1}^*(2700)^\pm$	1^-	$2708.3_{-3.4}^{+4.0}$	120 ± 11
$D_{s1}^*(2860)^\pm$	$1^- \dagger$	$2859 \pm 12 \pm 24$	$159 \pm 23 \pm 77$
$D_{s3}^*(2860)$	$3^- \dagger$	$2860.5 \pm 2.6 \pm 6.5$	$53 \pm 7 \pm 7$
$B_2^*(5747)$	2^+	5737.2 ± 0.7	20 ± 5
$B_{s1}(5830)^0$	1^+	5828.63 ± 0.27	$0.5 \pm 0.3 \pm 0.3$
$B_{s2}^*(5840)^0$	2^+	5839.84 ± 0.18	1.47 ± 0.33

TABLE I: Experimental total decay widths and masses of D , D_s , B and B_s mesons, extracted from the PDG [10]. States labeled by \dagger are omitted from the PDG summary table [10].

[20, 28, 29]

$$\Gamma_{A \rightarrow BC} = \Phi_{A \rightarrow BC}(q_0) \sum_{\ell} |\langle BC q_0 \ell J | T^\dagger | A \rangle|^2, \quad (1)$$

where the coefficient

$$\Phi_{A \rightarrow BC}(q_0) = 2\pi q_0 \frac{E_b(q_0)E_c(q_0)}{M_a}, \quad (2)$$

depending on the relative momentum q_0 and energies of the two decay products, $E_b = \sqrt{M_b^2 + q_0^2}$ and $E_c = \sqrt{M_c^2 + q_0^2}$, is the phase space factor for the decay. We assume harmonic oscillator wave functions, depending on a single oscillator parameter α . The final state is characterized by the relative orbital angular momentum ℓ between B and C and a total angular momentum $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$.

Following Refs. [34–36, 42], we introduce a few changes into the 3P_0 model operator, T^\dagger . These modifications include the substitution of the pair-creation strength, γ_0 , by an effective one [25, 34–36, 42],

$$\gamma_0^{\text{eff}} = \frac{m_n}{m_i} \gamma_0, \quad (3)$$

with $i = n$ (i.e. u or d), s , c and b (see Tables II and II), to suppress heavy quark pair-creation. Something similar was also done in Ref. [26], though the authors used a different form for γ_0^{eff} . We also introduce a Gaussian quark form-factor, because the pair of created quarks has an effective size [34–36, 42].

The values of the pair-creation model parameters for the $\text{SU}(4)_f$ and $\text{SU}(5)_f$ sectors, reported in Table II, are extracted from Refs. [34–36]. These are the values we use in our calculations.

Parameter	Value in $\text{SU}_f(4)$	Value in $\text{SU}_f(5)$
γ_0	0.510	0.732
α	0.500 GeV	0.500 GeV
r_q	0.335 fm	0.335 fm
m_n	0.330 GeV	0.330 GeV
m_s	0.550 GeV	0.550 GeV
m_c	1.50 GeV	1.50 GeV
m_b	–	4.70 GeV

TABLE II: Pair-creation model parameters for $\text{SU}_f(4)$ and $\text{SU}_f(5)$ sectors, from Refs. [34–36].

B. Godfrey and Isgur’s relativized quark model

The relativized quark model [40, 41] is based on an effective potential, whose dynamics is governed by a one-gluon exchange interaction at short distances plus a long-range linear confining one.

The Hamiltonian of the model is given by [40]

$$H = \sqrt{q^2 + m_1^2} + \sqrt{q^2 + m_2^2} + V_{\text{conf}} + V_{\text{hyp}} + V_{\text{so}}, \quad (4)$$

where m_1 and m_2 are the masses of the constituent quark and antiquark, q their relative momentum (with conjugate coordinate r), V_{conf} , V_{hyp} and V_{so} the confining, hyperfine and spin-orbit potentials, respectively.

The confining potential is the sum of three terms [40],

$$V_{\text{conf}} = - \left(\frac{3}{4} c + \frac{3}{4} br - \frac{\alpha_s(r)}{r} \right) \vec{F}_1 \cdot \vec{F}_2, \quad (5)$$

with $\langle q\bar{q} | \vec{F}_1 \cdot \vec{F}_2 | q\bar{q} \rangle = -\frac{4}{3}$. The first term is a constant, the second a spin-independent linear confining one, with parameter b , and the third a Coulomb-like interaction. The hyperfine interaction has the standard form [40]

$$V_{\text{hyp}} = -\frac{\alpha_s(r)}{m_1 m_2} \left[\frac{8\pi}{3} \vec{S}_1 \cdot \vec{S}_2 \delta^3(\vec{r}) + \frac{1}{r^3} \left(3 \frac{\vec{S}_1 \cdot \vec{r}}{r^2} \vec{S}_2 \cdot \vec{r} - \vec{S}_1 \cdot \vec{S}_2 \right) \right] \vec{F}_i \cdot \vec{F}_j. \quad (6)$$

The spin-orbit potential [40],

$$V_{\text{so}} = V_{\text{so,cm}} + V_{\text{so,tp}}, \quad (7)$$

is the sum of two contributions, where

$$V_{\text{so,cm}} = -\frac{\alpha_s(r)}{r^3} \left(\frac{1}{m_i} + \frac{1}{m_j} \right) \left(\frac{\vec{S}_i \cdot \vec{r}}{m_i} + \frac{\vec{S}_j \cdot \vec{r}}{m_j} \right) \cdot \vec{L} \vec{F}_i \cdot \vec{F}_j \quad (8a)$$

is the color-magnetic term and

$$V_{\text{so,tp}} = -\frac{1}{2r} \frac{\partial V_{ij,\text{conf}}}{\partial r} \left(\frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2} \right) \cdot \vec{L} \quad (8b)$$

the Thomas-precession one.

In the case of states characterized by quark and antiquark of unequal mass, charge conjugation is not a good

State	J^P	Mass [MeV]	$D\pi$	$D^*\pi$	$D\rho$	$D^*\rho$	$D\eta$	$D^*\eta$	$D\omega$	$D^*\omega$	D_sK	D_s^*K	D_sK^*	$D_s^*K^*$
$D^*(2007)$ or $D_1(1^3S_1)$	1^-	2038, 2009 [†]	0	–	–	–	–	–	–	–	–	–	–	–
$D_0^*(2400)$ or $D_0(1^3P_0)$	0^+	2398, 2318 [†]	66	–	–	–	–	–	–	–	–	–	–	–
$D_1(2420)$ or $D_1(1P_1)$	1^+	2456, 2421 [†]	–	32	–	–	–	–	–	–	–	–	–	–
$D_1(2430)$ or $D_1(1P_1')$	1^+	2467, 2427 [†]	–	37	–	–	–	–	–	–	–	–	–	–
$D_2^*(2460)$ or $D(1^3P_2)$	2^+	2501, 2463 [†]	6	2	–	–	0	–	–	–	–	–	–	–
$D_0(2550)$ or $D(2^1S_0)$	0^-	2582, 2564 [†]	–	45	–	–	–	0	–	–	–	–	–	–
$D_1(2^3S_1)$	1^-	2645	18	36	0	–	6	5	–	–	4	1	–	–
$D_1(1^3D_1)$	1^-	2816	20	13	13	1	10	5	4	0	6	2	–	–
$D_2(1D_2)$	2^-	2816	–	25	21	6	–	7	7	1	–	3	–	–
$D_3(1^3D_3)$	3^-	2833	11	8	1	15	2	1	0	4	1	0	–	–
$D_2(1D_2')$	2^-	2845	–	26	23	5	–	8	8	1	–	4	–	–
$D_1(2P_1)$	1^+	2924	–	26	20	33	–	7	7	11	–	4	6	–
$D_0(2^3P_0)$	0^+	2931	18	–	–	38	2	–	–	12	0	–	–	–
$D_2(2^3P_2)$	2^+	2957	13	23	22	45	6	7	7	16	4	4	1	–
$D_1(2P_1')$	1^+	2961	–	21	14	29	–	5	5	9	–	3	8	–
$D_0(3^1S_0)$	0^-	3067	–	1	4	38	–	1	1	13	–	3	8	8
$D_1(3^3S_1)$	1^-	3111	3	2	1	31	0	0	0	11	0	1	5	15
$D_4(1^3F_4)$	4^+	3113	11	8	4	36	2	1	1	12	1	0	0	1
$D_2(1^3F_2)$	2^+	3132	10	9	11	12	5	3	4	4	2	2	1	0
$D_2(2D_2)$	2^-	3212	–	15	15	30	–	5	5	10	–	3	3	5
$D_3(2^3D_3)$	3^-	3226	8	14	16	21	4	5	5	7	3	3	2	9
$D_2(2D_2')$	2^-	3248	–	14	13	32	–	4	4	11	–	3	3	4
$D_1(3P_1)$	1^+	3328	–	1	1	10	–	0	0	3	–	1	3	6
$D_1(2^3D_1)$	1^-	3231	7	2	0	51	1	0	0	17	0	0	1	4
$D_0(3^3P_0)$	0^+	3343	1	–	–	13	0	–	–	4	1	–	–	11
$D_2(3^3P_2)$	2^+	3352	2	1	0	13	0	0	0	5	0	1	1	6
$D_1(3P_1')$	1^+	3360	–	1	1	7	–	0	1	3	–	1	2	8
$D_3(1^3G_3)$	3^-	3398	5	2	7	15	2	2	2	5	1	1	1	1
$D_0(4^1S_0)$	0^-	3465	–	1	4	11	–	1	1	4	–	1	1	0
$D_4(2^3F_4)$	4^+	3466	5	8	10	12	2	3	3	4	2	2	2	4
$D_2(2^3F_2)$	2^+	3490	3	1	0	38	1	0	0	12	0	0	0	5
$D_2(3D_2)$	2^-	3566	–	1	1	3	–	0	0	1	–	1	1	3
$D_3(3^3D_3)$	3^-	3578	2	1	0	6	0	0	0	2	0	0	1	2
$D_2(3D_2')$	2^-	3600	–	1	1	3	–	0	0	1	–	1	1	3

TABLE III: Open-flavor strong decay widths (in MeV) for D states. Column 3 gives the values of the masses of the decaying mesons: when available, we use the experimental values from the PDG, denoted by the symbol [†] [10]; otherwise, we consider the predictions of the relativized QM for mesons [40]. Columns 4-15 show the decay width contributions (in MeV) from various channels, such as $D\pi$, $D^*\pi$, and so on. The values of the 3P_0 model parameters are given in Table II. The symbol – in the table means that a certain decay is forbidden by selection rules or that the decay cannot take place because it is below threshold. The calculated mixing angles are: $\theta_{1P} = 25.7^\circ$, $\theta_{2P} = 29.4^\circ$, $\theta_{3P} = 28.1^\circ$, $\theta_{1D} = 38.2^\circ$, $\theta_{2D} = 37.4^\circ$, $\theta_{3D} = 36.9^\circ$.

quantum number. Therefore, states with different spins but the same angular momentum, $|n^1L_J\rangle$ and $|n^3L_J\rangle$, can mix via the spin-orbit interaction. For example, this happens in the case of 1P_1 and 3P_1 states, where we consider the linear combinations

$$|nP\rangle = \cos\theta_{nP} |n^1P_1\rangle + \sin\theta_{nP} |n^3P_1\rangle \quad (9a)$$

and

$$|nP'\rangle = -\sin\theta_{nP} |n^1P_1\rangle + \cos\theta_{nP} |n^3P_1\rangle. \quad (9b)$$

For more details, see Refs. [40, 41].

The spectrum of open-charm and open-bottom states, obtained by solving the eigenvalue problem of Eq. (4) with the values of the model parameters of Ref. [40], is reported in Tables III-VII, third column.

III. RESULTS AND DISCUSSION

Below, we provide our 3P_0 model results for the open-flavor strong decays of open-charm (D and D_s) and open-bottom (B , B_s and B_c) mesons in the 3P_0 pair-creation model. The decays are computed according to the formalism of Sec. II A, with the values of the model parameters of Table II and Refs. [34–36]. When available, we calculate the amplitudes by using the experimental values of the meson masses, extracted from the PDG [10]; otherwise, we use the relativized QM predictions reported in the third column of Tables III–VII.

Finally, our results for charmed, charmed-strange, bottomed, bottomed-strange and bottomed-charm mesons are reported in Tables III, IV, V, VI and VII, respectively. See also Table I, which shows the existing experimental

State	J^P	Mass [MeV]	DK	D^*K	DK^*	D^*K^*	$D_s\eta'$	$D_s^*\eta'$	$D_s\phi$	$D_s^*\phi$
$D_{s1}(2460)$ or $D_{s1}(1P_1)$	1^+	2549, 2459.5 [†]	—	— (46)	—	—	—	—	—	—
$D_{s1}(2536)$ or $D_{s1}(1P_1')$	1^+	2556, 2535.10 [†]	—	56 (54)	—	—	—	—	—	—
$D_{s2}^*(2573)$ or $D_{s2}(1^3P_2)$	2^+	2591, 2569.1 [†]	4	0	—	—	—	—	—	—
$D_{s0}(2^1S_0)$	0^-	2675	—	53	—	—	—	—	—	—
$D_{s1}^*(2700)$ or $D_{s1}(2^3S_1)$	1^-	2735, 2708.3 [†]	28	42	—	—	—	—	—	—
$D_{s1}^*(2860)$ or $D_{s1}(1^3D_1)$	1^-	2898, 2859 [†]	43	23	13	—	—	—	—	—
$D_{s3}^*(2860)$ or $D_{s3}(1^3D_3)$	3^-	2916, 2860.5 [†]	10 (14)	5 (8)	0 (1)	— (5)	—	—	—	—
$D_{s2}(1D_2)$	2^-	2900	—	40	31	1	—	—	—	—
$D_{s2}(1D_2')$	2^-	2926	—	43	34	1	—	—	—	—
$D_{s0}(2^3P_0)$	0^+	3005	28	—	—	51	14	—	—	—
$D_{s1}(2P_1)$	1^+	3018	—	37	27	44	—	—	7	—
$D_{s1}(2P_1')$	1^+	3038	—	31	20	35	—	—	10	—
$D_{s2}(2^3P_2)$	2^+	3049	19	33	31	64	1	—	0	—
$D_{s0}(3^1S_0)$	0^-	3153	—	2	3	50	—	6	8	3
$D_{s4}(1^3F_4)$	4^+	3190	17	11	5	60	0	0	0	0
$D_{s1}(3^3S_1)$	1^-	3194	6	3	0	39	2	5	5	11
$D_{s2}(1^3F_2)$	2^+	3208	21	17	19	18	3	1	1	4
$D_{s2}(2D_2)$	2^-	3298	—	24	22	44	—	3	3	5
$D_{s1}(2^3D_1)$	1^-	3306	13	3	1	74	1	2	1	4
$D_{s3}(2^3D_3)$	3^-	3311	2	20	23	29	2	1	2	10
$D_{s2}(2D_2')$	2^-	3323	—	22	21	47	—	3	3	5
$D_{s0}(3^3P_0)$	0^+	3412	3	—	—	15	2	—	—	12
$D_{s1}(3P_1)$	1^+	3416	—	3	1	10	—	3	3	7
$D_{s1}(3P_1')$	1^+	3433	—	2	1	7	—	3	2	8
$D_{s2}(3^3P_2)$	2^+	3439	6	3	1	14	1	2	1	6
$D_{s3}(1^3G_3)$	3^-	3469	12	12	13	27	2	1	1	1
$D_{s0}(4^1S_0)$	0^-	3544	—	1	4	16	—	1	1	1
$D_{s4}(2^3F_4)$	4^+	3544	7	12	15	18	2	1	2	5
$D_{s2}(2^3F_2)$	2^+	3562	8	3	2	59	0	0	0	6
$D_{s2}(3D_2)$	2^-	3650	—	3	2	3	—	1	1	3
$D_{s3}(3^3D_3)$	3^-	3661	5	3	1	7	0	1	0	3
$D_{s2}(3D_2')$	2^-	3672	—	3	1	3	—	1	1	3

TABLE IV: As Table III, but for D_s mesons. The calculated mixing angles are: $\theta_{1P} = 37.5^\circ$, $\theta_{2P} = 30.4^\circ$, $\theta_{3P} = 27.7^\circ$, $\theta_{1D} = 38.5^\circ$, $\theta_{2D} = 37.7^\circ$, $\theta_{3D} = 37.2^\circ$. In the $1P_1 - 1P_1'$ and $D_{s3}^*(2860)$ cases, the values in parentheses are calculated by using the relativized QM predictions for the decaying meson masses.

data for the total widths of D , D_s , B and B_s resonances. There are no data available for higher B_c resonances [10].

Our theoretical results of Tables III–VII reproduce the global trend of the PDG data [10] (see also Table I), with a few exceptions.

In more detail, starting from the D sector, our result for the open-flavor width of the $D^*(2007)^0$, $\Gamma_{\text{of}}^{\text{th}} = 4$ keV, is compatible with the total experimental width $\Gamma_{\text{tot}}^{\text{exp}} < 2.1$ MeV [10]. A more refined prediction would require the introduction of coupled-channel effects, the mass of the $D^*(2007)^0$ being very close to $D\pi$ threshold. The same applies to $D_0^*(2400)$, where the presence of higher Fock components in the meson wave function may lower the relativized QM prediction for the mass, 2398 MeV, down to the experimental value, 2318 ± 29 MeV, and also contribute to the open-flavor amplitude. In the $D_1(2420)$ case, which should mainly decay into $D^*\pi$ with the possible chain $D^*\pi \rightarrow D\pi\pi$, our 3P_0 model prediction is compatible with the data, while this is not true for $D_1(2430)$, being $\Gamma_{\text{of}}^{\text{th}} \ll \Gamma_{\text{tot}}^{\text{exp}}$. Nevertheless, it is worth noting that, in this second case, the experimental error

is still very large; moreover, if $D_1(2420)$ and $D_1(2430)$ are mixed by spin-orbit forces, their open-flavor widths are likely to be of the same order of magnitude. Our results for the total open-flavor widths of $D_2^*(2460)$ and $D_0(2550)$ are compatible with the present experimental data, being $\Gamma_{\text{of}}^{\text{th}} < \Gamma_{\text{tot}}^{\text{exp}}$; there is no experimental information on the partial open-flavor widths. Coupled-channel effects may play an important role in the $D_2^*(2460)$ case, which is very close to $D\eta$ and D_sK thresholds.

Moving to the D_s sector, our predictions for $D_{s1}(2460)$ are compatible with the data [10], while those for $D_{s1}(2536)$ are not. The former meson has a narrow width and mainly decays to D_s^* via photon or π^0 emission, which are normally suppressed decay modes [50]. Because of the large mass difference between $D_{s1}(2460)$ and $D_{s1}(2536)$, which cannot be explained in terms of hyperfine or spin-orbit splittings, these mesons may have exotic nature. Our results for the total widths of $D_{s2}^*(2573)$, $D_{s1}^*(2700)$, $D_{s1}^*(2860)$ and $D_{s3}^*(2860)$ are compatible with the experimental data [10], being $\Gamma_{\text{of}}^{\text{th}} < \Gamma_{\text{tot}}^{\text{exp}}$. We cannot say much on the single channels, as the PDG only

State	J^P	Mass [MeV]	$B\pi$	$B^*\pi$	$B\rho$	$B^*\rho$	$B\eta$	$B^*\eta$	$B\omega$	$B^*\omega$	$B_s K$	$B_s^* K$	$B_s K^*$	$B_s^* K^*$
$B_2^*(5747)$ or $B_2(1^3P_2)$	2^+	5796, 5738 [†]	4	3	—	—	—	—	—	—	—	—	—	—
$B_0(1^3P_0)$	0^+	5756	117	—	—	—	—	—	—	—	—	—	—	—
$B_1(1P_1)$	1^+	5777	—	55	—	—	—	—	—	—	—	—	—	—
$B_1(1P_1')$	1^+	5784	—	73	—	—	—	—	—	—	—	—	—	—
$B_0(2^1S_0)$	0^-	5905	—	87	—	—	—	4	—	—	—	—	—	—
$B_1(2^3S_1)$	1^-	5934	30	60	—	—	7	6	—	—	3	1	—	—
$B_2(1D_2)$	2^-	6095	—	49	16	1	—	15	4	0	—	7	—	—
$B_3(1^3D_3)$	3^-	6105	16	16	0	1	1	1	0	—	0	0	—	—
$B_1(1^3D_1)$	1^-	6110	42	23	11	1	21	10	3	0	11	5	—	—
$B_2(1D_2')$	2^-	6124	—	50	17	2	—	16	5	0	—	8	—	—
$B_1(2P_1)$	1^+	6197	—	46	31	58	—	12	10	19	—	7	—	—
$B_2(2^3P_2)$	2^+	6213	22	35	21	99	9	13	7	35	6	7	—	—
$B_0(2^3P_0)$	0^+	6214	35	—	—	70	3	—	—	22	0	—	—	—
$B_1(2P_1')$	1^+	6228	—	42	29	48	—	10	10	15	—	5	—	—
$B_0(3^1S_0)$	0^-	6334	—	11	16	59	—	0	6	21	—	2	11	6
$B_1(3^3S_1)$	1^-	6355	6	9	7	53	0	0	3	19	0	1	9	16
$B_4(1^3F_4)$	4^+	6364	19	20	4	80	3	3	1	26	1	1	0	1
$B_2(1^3F_2)$	2^+	6387	20	15	23	27	10	7	8	9	5	4	1	0
$B_2(2D_2)$	2^-	6450	—	25	24	56	—	9	8	19	—	5	5	9
$B_3(2^3D_3)$	3^-	6459	12	18	26	37	6	9	8	12	4	5	2	17
$B_1(2^3D_1)$	1^-	6475	15	6	0	100	3	1	0	33	0	0	2	7
$B_2(2D_2')$	2^-	6486	—	25	22	60	—	8	7	20	—	4	6	8
$B_1(3P_1)$	1^+	6557	—	7	3	9	—	0	1	3	—	1	5	11
$B_2(3^3P_2)$	2^+	6570	6	7	0	16	1	0	0	6	0	0	3	10
$B_1(3P_1')$	1^+	6585	—	7	3	5	—	0	1	2	—	1	4	12
$B_0(3^3P_0)$	0^+	6590	6	—	—	5	0	—	—	2	0	—	—	18
$B_3(1^3G_3)$	3^-	6622	10	9	15	38	5	4	5	12	2	2	2	2
$B_4(2^3F_4)$	4^+	6679	5	9	17	22	3	5	6	7	2	3	2	7
$B_0(4^1S_0)$	0^-	6687	—	0	6	16	—	1	2	5	—	1	2	2
$B_2(2^3F_2)$	2^+	6704	9	5	12	69	2	1	0	23	0	0	0	9
$B_2(3D_2)$	2^-	6767	—	6	1	2	—	1	0	1	—	0	1	4
$B_3(3^3D_3)$	3^-	6775	5	5	1	6	1	1	0	2	0	0	1	4
$B_2(3D_2')$	2^-	6800	—	5	1	2	—	1	0	1	—	0	1	4
$B_3(2^3G_3)$	3^-	6909	5	4	2	38	1	1	0	13	0	0	0	7
$B_0(4^3P_0)$	0^+	6954	1	—	—	3	0	—	—	1	0	—	—	3
$B_4(3^3F_4)$	4^+	6966	3	4	1	3	1	1	0	1	0	0	0	2
$B_4(4^3F_4)$	4^+	7230	0	0	0	2	0	0	0	1	0	0	0	0

TABLE V: As Table III, but for B mesons. The calculated mixing angles are: $\theta_{1P} = 30.3^\circ$, $\theta_{2P} = 32.3^\circ$, $\theta_{3P} = 31.6^\circ$, $\theta_{1D} = 39.7^\circ$, $\theta_{2D} = 39.0^\circ$, $\theta_{3D} = 38.6^\circ$.

provides some preliminary results for a few branching fractions, except that, in the $D_{s2}^*(2573)$ case, our predictions are compatible with $\Gamma(D^*K)/\Gamma(DK) < 0.33$ [10]. In the $D_{s3}^*(2860)$ case, we also show predictions extracted by using the relativized QM mass for the decaying meson because: I) There is a large difference between experimental and calculated masses; II) The experimental data are not very reliable as, at the moment, the state is excluded from the PDG summary table [10].

Finally, we discuss our predictions for the B and B_s sectors. Our results for the total open-flavor widths of $B_2^*(5747)$ and $B_{s2}^*(5840)$ and for the ratio $\frac{\Gamma(B_2^*(5747) \rightarrow B^*\pi)}{\Gamma(B_2^*(5747) \rightarrow B\pi)}$ are compatible with the experimental data [10, 51]. By contrast, our result for the open-flavor width of $B_{s1}(5830)$ is incompatible with the data. Our prediction is very sensitive to the value of the decaying meson mass – as $B_{s1}(5830)$ is close to the B^*K threshold

– and thus a few MeV mass difference can produce large deviations in the calculated decay amplitude.

IV. SUMMARY AND CONCLUSION

We computed the open-flavor strong decays of open-charm and open-bottom mesons within a modified version of the 3P_0 pair-creation model [20, 29].

In the 3P_0 model, the open-flavor decays take place in the rest frame of the initial state, via the production of a light $q\bar{q}$ pair (i.e. $q = u, d$ or s) with 3P_0 quantum numbers. Heavy quark pair production is heavily suppressed, as required by the phenomenology, by substituting the pair-creation strength, γ_0 , with an effective one, γ_0^{eff} [25, 34–36, 42]. Moreover, the non-point-like nature of the pair of produced quarks is taken into account by

State	J^P	Mass [MeV]	BK	B^*K	BK^*	B^*K^*	$B_s\eta'$	$B_s^*\eta'$	$B_s\phi$	$B_s^*\phi$
$B_{s1}(5830)$ or $B_{s1}(1P_1)$	1^+	5857, 5828.63	—	85 (30)	—	—	—	—	—	—
$B_{s0}(1^3P_0)$	0^+	5830	208	—	—	—	—	—	—	—
$B_{s2}^*(5840)$ or $B_{s2}(1^3P_2)$	2^+	5875, 5839.84 [†]	1	0	—	—	—	—	—	—
$B_{s1}(1P_1')$	1^+	5861	—	98	—	—	—	—	—	—
$B_{s0}(2^1S_0)$	0^-	5985	—	106	—	—	—	—	—	—
$B_{s1}(2^3S_1)$	1^-	6013	46	81	—	—	—	—	—	—
$B_{s2}(1D_2)$	2^-	6169	—	82	3	—	—	—	—	—
$B_{s3}(1^3D_3)$	3^-	6178	17	16	0	—	—	—	—	—
$B_{s1}(1^3D_1)$	1^-	6181	89	47	1	—	—	—	—	—
$B_{s2}(1D_2')$	2^-	6196	—	86	3	—	—	—	—	—
$B_{s0}(2^3P_0)$	0^+	6279	52	—	—	71	—	—	—	—
$B_{s1}(2P_1)$	1^+	6279	—	70	47	81	—	—	—	—
$B_{s2}(2^3P_2)$	2^+	6295	35	56	24	172	—	—	—	—
$B_{s1}(2P_1')$	1^+	6296	—	63	49	51	—	—	—	—
$B_{s0}(3^1S_0)$	0^-	6409	—	16	24	92	—	6	4	—
$B_{s1}(3^3S_1)$	1^-	6429	10	21	10	84	5	6	6	—
$B_{s4}(1^3F_4)$	4^+	6431	28	27	4	125	0	0	0	—
$B_{s2}(1^3F_2)$	2^+	6453	46	34	39	38	3	1	1	0
$B_{s2}(2D_2)$	2^-	6526	—	44	36	83	—	6	7	9
$B_{s3}(2^3D_3)$	3^-	6534	18	29	39	53	2	1	1	20
$B_{s1}(2^3D_1)$	1^-	6542	31	13	0	145	4	3	4	6
$B_{s2}(2D_2')$	2^-	6553	—	43	33	87	—	7	7	8
$B_{s1}(3P_1)$	1^+	6635	—	16	3	10	—	5	5	12
$B_{s0}(3^3P_0)$	0^+	6638	13	—	—	10	5	—	—	21
$B_{s2}(3^3P_2)$	2^+	6647	12	14	0	19	2	4	4	11
$B_{s1}(3P_1')$	1^+	6650	—	14	4	5	—	5	5	14
$B_{s3}(1^3G_3)$	3^-	6685	26	22	31	67	4	2	2	2
$B_{s4}(2^3F_4)$	4^+	6747	7	13	26	37	3	3	3	9
$B_{s0}(4^1S_0)$	0^-	6757	—	2	6	22	—	2	2	2
$B_{s2}(2^3F_2)$	2^+	6768	21	13	4	110	0	1	1	11
$B_{s2}(3D_2)$	2^-	6841	—	15	4	5	—	2	2	5
$B_{s3}(3^3D_3)$	3^-	6848	10	12	4	7	0	1	1	6
$B_{s2}(3D_2')$	2^-	6864	—	14	3	5	—	2	2	5
$B_{s0}(4^3P_0)$	0^+	6949	2	—	—	10	1	—	—	4
$B_{s3}(2^3G_3)$	3^-	6970	15	10	6	62	0	0	0	10
$B_{s4}(3^3F_4)$	4^+	7034	8	9	5	5	0	0	0	3
$B_{s4}(4^3F_4)$	4^+	7297	3	2	0	3	0	0	0	1

TABLE VI: As Table III, but for B_s mesons. The calculated mixing angles are: $\theta_{1P} = 39.1^\circ$, $\theta_{2P} = 33.1^\circ$, $\theta_{3P} = 31.6^\circ$, $\theta_{1D} = 40.0^\circ$, $\theta_{2D} = 39.5^\circ$, $\theta_{3D} = 39.1^\circ$. In the $B_{s1}(5830)$ case, the value in brackets is calculated by using the experimental value for the mass, without mixing with $B_{s1}(1P_1')$.

introducing a quark form-factor [34–36, 42, 52–56] into the model transition operator. The values of the 3P_0 model parameters in the $SU_f(4)$ and $SU_f(5)$ sectors were extracted from our previous studies on $c\bar{c}$ [34, 35] and $b\bar{b}$ [35, 36] meson spectroscopy and decays, where they were fitted to the existing experimental data [10].

The open-charm and open-bottom meson spectra we needed in our calculation were predicted within Godfrey and Isgur’s relativized quark model [40]. This is one of the most powerful tools for the study of $q\bar{q}$ meson spectroscopy, and provides a description of the meson spectrum in the light, strange, $c\bar{c}$, ..., sectors with a universal set of parameters; moreover, 30 years since its formulation, it still gives a good overall description of the experimental data.

As discussed in our previous papers [34–36], there may

be substantial deviations between the experimental values of the masses and QM predictions [40] in the case of resonances lying close to meson-meson decay thresholds. In these cases, continuum coupling effects may be important and determine a downward energy shift for the bare meson masses, thus improving the fit to the data; coupled-channel effects may also contribute to the open-flavor amplitudes. Such mesons may have an exotic nature, such as tetraquarks, meson-meson molecules or $q\bar{q}$ mesons plus continuum components. For example, this may be the case of $D(1^3S_1)$, $D_0^*(2400)$ and $D_{s0}^*(2317)$ [43, 44], where QM predictions are incompatible with the present experimental data [10]. The possible interpretations for suspected exotic open-charm and open-bottom mesons will be discussed in a future paper.

In conclusion, we think that our predictions can be

State	J^P	Mass [MeV]	BD	B^*D	BD^*	B^*D^*	B_sD_s	$B_s^*D_s$	$B_sD_s^*$	$B_s^*D_s^*$
$B_{c2}(2^3P_2)$	2^+	7164	2	—	—	—	—	—	—	—
$B_{c0}(3^1S_0)$	0^-	7249	—	107	—	—	—	—	—	—
$B_{c2}(1^3F_2)$	2^+	7269	90	29	—	—	—	—	—	—
$B_{c4}(1^3F_4)$	4^+	7271	3	1	—	—	—	—	—	—
$B_{c1}(3^3S_1)$	1^-	7272	13	64	—	—	—	—	—	—
$B_{c1}(2^3D_1)$	1^-	7365	3	2	37	27	10	—	—	—
$B_{c3}(2^3D_3)$	3^-	7379	46	52	15	184	0	—	—	—
$B_{c0}(3^3P_0)$	0^+	7454	0	—	—	157	4	—	—	—
$B_{c3}(1^3G_3)$	3^-	7474	93	66	45	27	5	1	—	—
$B_{c2}(3^3P_2)$	2^+	7487	10	4	7	105	4	7	0	—
$B_{c2}(2^3F_2)$	2^+	7565	36	13	0	133	1	3	4	1
$B_{c0}(4^1S_0)$	0^-	7567	—	2	23	55	—	2	2	14
$B_{c4}(2^3F_4)$	4^+	7568	21	34	39	52	4	3	0	6
$B_{c3}(3^3D_3)$	3^-	7669	20	20	6	19	0	1	3	5
$B_{c0}(4^3P_0)$	0^+	7740	4	—	—	22	3	—	—	1
$B_{c3}(2^3G_3)$	3^-	7743	42	25	12	104	0	0	1	9
$B_{c4}(3^3F_4)$	4^+	7834	15	19	15	12	1	0	0	6
$B_{c4}(4^3F_4)$	4^+	8077	10	12	7	6	0	0	0	3

TABLE VII: As Table III, but for B_c mesons.

useful to the experimentalists in their study of the properties of open-charm and open-bottom mesons and in the search for new resonances.

Flavor couplings in the 3P_0 pair-creation model

In the following, we show how to calculate the $SU_f(5)$ flavor couplings of the 3P_0 pair-creation model. The $SU_f(4)$ couplings can be computed analogously.

We consider the transition $A \rightarrow BC$, where A , B and C are quark-antiquark mesons. The $SU_f(5)$ flavor couplings can be written as the scalar product between initial, $|A(q_1\bar{q}_2)\Phi_0(q_3\bar{q}_4)\rangle$, and final states, $|B(q_1\bar{q}_4)C(q_3\bar{q}_2)\rangle$, where Φ_0 is the $SU_f(5)$ flavor singlet

$$|\Phi_0\rangle = \frac{1}{\sqrt{n_f}} \sum_{i=1}^{n_f} q_3^i \bar{q}_4^i = \frac{1}{\sqrt{5}} (|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle + |c\bar{c}\rangle + |b\bar{b}\rangle) \quad (10)$$

and $n_f = 5$ is the dimension of the SU_f flavor group. In general, two different diagrams can contribute to the flavor matrix element $\langle BC|A\Phi_0\rangle$: in the first one, the quark in A ends up in B , while in the second one it ends up in C . In the majority of cases, one of these two

diagrams vanishes; however, for some matrix elements, both must be taken into account [34–36, 42]. Finally, the flavor matrix elements can be calculated as:

$$\begin{aligned} & [\langle q_1\bar{q}_4 | \otimes \langle q_3\bar{q}_2 |] \left[|q_1\bar{q}_2\rangle \otimes \frac{1}{\sqrt{n_f}} \sum_{i=1}^{n_f} |q_3^i \bar{q}_4^i\rangle \right] \\ &= \frac{1}{\sqrt{n_f}} \sum_{i=1}^{n_f} [\langle q_1\bar{q}_4 q_3 \bar{q}_2 | q_1 \bar{q}_2 q_3^i \bar{q}_4^i \rangle \\ &+ \langle q_3 \bar{q}_2 q_1 \bar{q}_4 | q_1 \bar{q}_2 q_3^i \bar{q}_4^i \rangle] \end{aligned} \quad (11)$$

As an example, we calculate the $B^0 \rightarrow B^0 \pi^0$ flavor coupling. The flavor matrix element can be written as

$$\begin{aligned} & \langle B^0 \pi^0 | B^0 \Phi_0 \rangle_{\text{flavor}} \\ &= -\frac{1}{\sqrt{10}} [\langle d\bar{b}d\bar{d} | d\bar{b}d\bar{d} \rangle + \langle d\bar{d}d\bar{b} | d\bar{b}d\bar{d} \rangle \\ &- \langle d\bar{b}u\bar{u} | d\bar{b}u\bar{u} \rangle + \dots] = -\frac{1}{\sqrt{10}} \end{aligned} \quad (12)$$

The only surviving contribution in Eq. (12) is $\langle d\bar{d}d\bar{b} | d\bar{b}d\bar{d} \rangle$; the others, like $\langle d\bar{b}d\bar{d} | d\bar{b}d\bar{d} \rangle$ or $\langle d\bar{b}u\bar{u} | d\bar{b}u\bar{u} \rangle$, are null [see Eq. (11)]. In conclusion, after dividing Eq. (12) by the corresponding $SU(2)$ Clebsch-Gordan coefficient, we get

$$\langle B\pi | B\Phi_0 \rangle_{\text{flavor}} = -\sqrt{\frac{3}{10}}. \quad (13)$$

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